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Review

Estimation of the hip joint centre in human motion analysis: A systematic review

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ABSTRACT

Background: Inaccuracies in locating the three-dimensional position of the hip joint centre affect the calculated hip and knee kinematics, force- and moment-generating capacity of muscles and hip joint mechanics, which can lead to incorrect interpretations and recommendations in gait analysis. Several functional and predictive methods have been developed to estimate the hip joint centre location, and the International Society of Biomechanics recommends a functional approach for use with participants that have adequate range of motion at the hip, and predictive methods in those with insufficient range of motion. The purpose of the current systematic review was to substantiate the International Society of Biomechanics recommendations. This included identifying the most accurate functional and predictive methods, and defining 'adequate' range of motion.
Methods: A systematic search with broad search terms was performed including five databases.
Findings: The systematic search yielded to 801 articles, of which 34 papers were included. Eleven different predictive and 13 different functional methods were identified. The results showed that the geometric sphere fit method and Harrington equations are the most accurate functional and predictive approaches respectively that have been evaluated in vivo.
Interpretation: In regard to the International Society of Biomechanics recommendations, the geometric sphere fit method should be used in people with sufficient active hip range of motion and the Harrington equations should be used in patients without sufficient hip range of motion. Multi-plane movement trials with at least 60° of flexion–extension and 30° of ab-adduction range of motion are suggested when using functional methods.

1. Introduction

Accurate measurement of human movement is important for the assessment of pathological gait patterns (e.g. in children with cerebral palsy), prediction of musculoskeletal loading, and evaluation of clinical intervention outcomes (Ehrig et al., 2011; Lopomo et al., 2010). Most clinical gait laboratories use commercially available biomechanical models, which are based on variants of traditional gait analysis models (Davis et al., 1991; Kadaba et al., 1990). Major sources of error that influence the accuracy of these models include: (1) errors in locating anatomical landmarks, (2) soft tissue artefact, and (3) definitions of joint centres and axes (Peters et al., 2010a; Scheys et al., 2011). The current review focussed on the latter error source, and provides an overview of the approaches used to estimate the hip joint centre (HJC).

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The HJC is involved in defining the hip and knee joint co-ordinate systems. Therefore, errors in locating the three-dimensional (3D) position of the HJC affect calculated gait analysis variables. These include the hip and knee joint moments (Pohl et al., 2010; Stagni et al., 2000), force- and moment-generating capacity of muscles (Delp and Maloney, 1993; Delp et al., 1994) and hip contact forces (Lenaerts et al., 2009), which can lead to incorrect interpretations and recommendations in clinical gait analysis. Some research groups have found differences in kinematic and kinetic data between traditionally used models, rescaled generic models, and medical imaging based models (Lenaerts et al., 2009; Scheys et al., 2011). Medical imaging-based methods, with individualized hip joint geometry and 3D HJC location, are therefore recommended to be used to obtain accurate kinematic data (Lenaerts et al., 2009). Due to high costs, ionising radiation risk and/or long post-processing time, medical imaging is, however, not routinely collected on patients. Therefore, efforts to improve joint centre and axes determination using alternative methods, such as functional and predictive approaches, are warranted (Scheys et al., 2011).

In the traditional gait analysis model (Davis et al., 1991; Kadaba et al., 1990) the position of the HJC with respect to the pelvis is determined by predictive methods. Predictive methods use regression equations based on experimental data from medical imaging (e.g. Bell et al., 1990; Davis et al., 1991) or cadaveric studies (e.g. Seidel et al., 1995). Alternatively, functional methods use kinematics and geometrical constraints, and can be divided into transformation techniques (e.g. Siston and Delp, 2006) and sphere fitting techniques (e.g. Leardini et al., 1999), following the terminology of Ehrig et al. (2006).

The International Society of Biomechanics (ISB) recommends a functional approach for estimating the position of the HJC in participants with adequate hip range of motion (ROM), and predictive methods in people with insufficient hip ROM (Wu et al., 2002). No further details are provided regarding which of the numerous functional or predictive methods should be selected, nor what comprises sufficient ROM. Therefore, the aim of the present review was to evaluate the evidence describing the accuracy and reliability of methods to estimate the 3D position of the HJC with the view of clarifying and detailing current ISB recommendations.

2. Method

2.1. Study identification and selection

A systematic search was performed of computerised databases, including MEDLINE (via PubMed), CINAHL, EMBASE, Web of Science, and the Cochrane Library (up till September 2014). The search strategy included the following title/abstract search strings: “three dimensional motion analysis” OR “three dimensional gait analysis” OR “3D motion analysis” OR “3D gait analysis” OR “3DGA” OR “kinematic model” OR “generic model” OR “subject specific model” OR “joint center” OR “joint centre” OR “joint axis”. The search was narrowed by combining the latter search terms with the following title and abstract search terminologies: “accuracy” OR “reliability” OR “validity”. References and abstracts of studies were stored alphabetically into EndNote X6 (Thomson Reuters, New York, USA).

The resulting EndNote bibliographies were then manually searched for the final set of papers to be included in the systematic review. First, duplicate references from different databases were removed. Second, papers were included if they met the a priori inclusion criteria. In this process, the titles and abstracts were evaluated by two independent reviewers (H.K. and C.C.) for inclusion. When the title and abstract failed to indicate whether an article should be included then the full text was obtained and reviewed. Any disagreement between the two reviewers was resolved by consensus. The inclusion criteria used were: (1) 3D motion analysis studies; (2) any report of accuracy, reliability (within tester, between testers and between days) or validity in the context of the calculation or estimation of human hip joint centres and axes; (3) full papers; and (4) published in English or German. In this context 3D motion analysis related studies refer to a stationary 3D gait analysis system (fixed cameras and fixed force plates) with at least two cameras without any zooming during the motion capturing and a marker based motion capturing. Each paper was then assessed for quality.

2.2. Quality assessment

The quality of literature was evaluated based on a previously established customised quality assessment tool by Peters et al. (2010a). This consists of 19 appraisal questions and was developed for systematic reviews in the field of human motion analysis. Questions were related to the description or justification of objectives (1); study design (2); participant characteristics (3); sample size (4 and 5); marker locations (6 and 7); equipment (8); the type and ROM of functional movement task (9); gold standard and analytical techniques (10 and 11); statistics (12); outcomes (13); results (14 and 15); key findings (16 and 17); limitations (18); and conclusions (19). Each question was rated zero, one or two, which indicated no information, limited details and satisfying information respectively. Two reviewers (H.K. and C.C.) independently assessed each article. Any discrepancy between the two reviewers was resolved by a consensus meeting.

2.3. Terminology

Accuracy, in the context of this study, is defined as a measure of the error in the estimation of the 3D HJC position with respect to a gold standard (e.g. medical imaging technique). Reliability describes the within tester, between testers, and between days variation in HJC estimate results for each method. Precision is defined as the repeatability of a measurement under unchanged conditions and is reported as the standard deviation of the HJC estimation errors in the current study.

As can be appreciated there are many different approaches being evaluated in this review, such as numerical algorithms and functional movement tasks. Therefore, in an attempt to be consistent with the literature, we employed an extended version of the terminology and acronyms from Ehrig et al. (2006) (see caption of Table 2).

3. Results

3.1. Study inclusion

The electronic search yielded to 801 articles without any duplicates. Following the application of the inclusion criteria 34 papers were included in the systematic review (Fig. 1). These papers were divided into in vivo, cadaveric, simulation, mechanical linkage, and theoretical studies. Seventeen of the studies were in vivo studies. These studies included an average of 19.3 (SD 16.7; range: 6–70) participants. Most in vivo investigations (13 out of 17) only included healthy participants (Bell et al., 1990; Besier et al., 2003; Hicks and Richards, 2005; Kirkwood et al., 1999; Kratzenstein et al., 2012; Leardini et al., 1999; Piazza et al., 2004; Pohl et al., 2010; Sangeux et al., 2011, 2014; Taylor et al., 2010; Weinhandl and O'Connor, 2010; Bell et al., 1989). Four studies focussed on people with pathologies. Two of these four studies were done with hip arthroplasty patients (Andersen et al., 2013; Heller et al., 2011) and the other two studies focussed on children with cerebral palsy (CP) (Harrington et al., 2007; Peters et al., 2012). One of the studies with children with CP included healthy individuals as well (Harrington et al., 2007). Four studies were done with cadavers. Three of these studies (Cereatti et al., 2009; De Momi et al., 2009; Lopomo et al., 2010) used four specimens and one study used 65 specimens (Seidel et al., 1995). One research group did an in vivo and ex vivo examination of the same participant (McGibbon et al., 1997). Seven simulation studies (Begon et al., 2007; Camomilla et al., 2006; Ehrig et al., 2006; Gamage and Lasenby, 2002; Halvorsen, 2003; Lu, 2000) and four mechanical linkage studies (MacWilliams, 2008; Piazza et al., 2001; Schwartz and Rozumalski, 2005; Siston and Delp, 2006) were included in the review. One theoretical study (Cereatti et al., 2004) focussed on the mathematical background of two functional methods to estimate the HJC was also included. Details of all included articles are provided in Table 1.

The methods used to estimate the HJC in all included studies could be categorised into predictive and functional approaches: eleven predictive and 13 functional (Table 2). Nevertheless, a meta-analysis of the results was not considered to be appropriate due to diversity of studies (in vivo, cadaver, simulation, mechanical linkage, and theoretical studies) within the functional and predictive method categories. The review therefore comprised a qualitative descriptive analysis of the research available, also known as “best evidence synthesis” (Deville et al., 2002).

3.2. Quality of studies

Some of the quality assessment questions were not applicable to all papers due to the study design (e.g. simulation or mechanical linkage study without participants). Hence, overall score of each article was